

WASTED WIND

Designed for this...

...but experience this.



This aerial photo of Denmark's Horns Rev 1 offshore wind farm was captured just as weather conditions created fog in the wake of each wind turbine. The more turbulent downstream air can cause power losses and mechanical problems for turbines behind the front row.

CREDIT: Christian Steiness/Vattenfall

“WHY AREN’T THEY TURNING?”

It’s a windy day, and even though some of the wind farm’s turbines appear to be turning as they were designed to, many are barely turning, and several aren’t turning at all. It looks as though a lot of energy is going to waste.

Indeed, each of the massive, state-of-the-art turbines is designed to extract several megawatts (MW) of energy from the wind, with the largest capable of generating 7.5 MW. That’s enough power from one turbine to provide for more than 700 average Americans on an ongoing basis, and 100 such turbines would out-produce some nuclear power plants. Yet these wind turbines routinely underperform their predicted power output and suffer mechanical failures that prevent them from turning at all. According to the U.S. National Renewable Energy Laboratory, wind farms typically perform at 10 percent below expectations—and sometimes as much as 40 percent below.

Meanwhile, the demand for wind power to reduce humanity’s reliance on fossil fuels continues to grow. And in a way, that’s part of the problem. Because as the demand has grown, so too have the turbines themselves. This was not unexpected, since the power they collect is proportional to the area of the circle swept out by their blades. Bigger should mean better. But great size brings unexpected vulnerabilities.

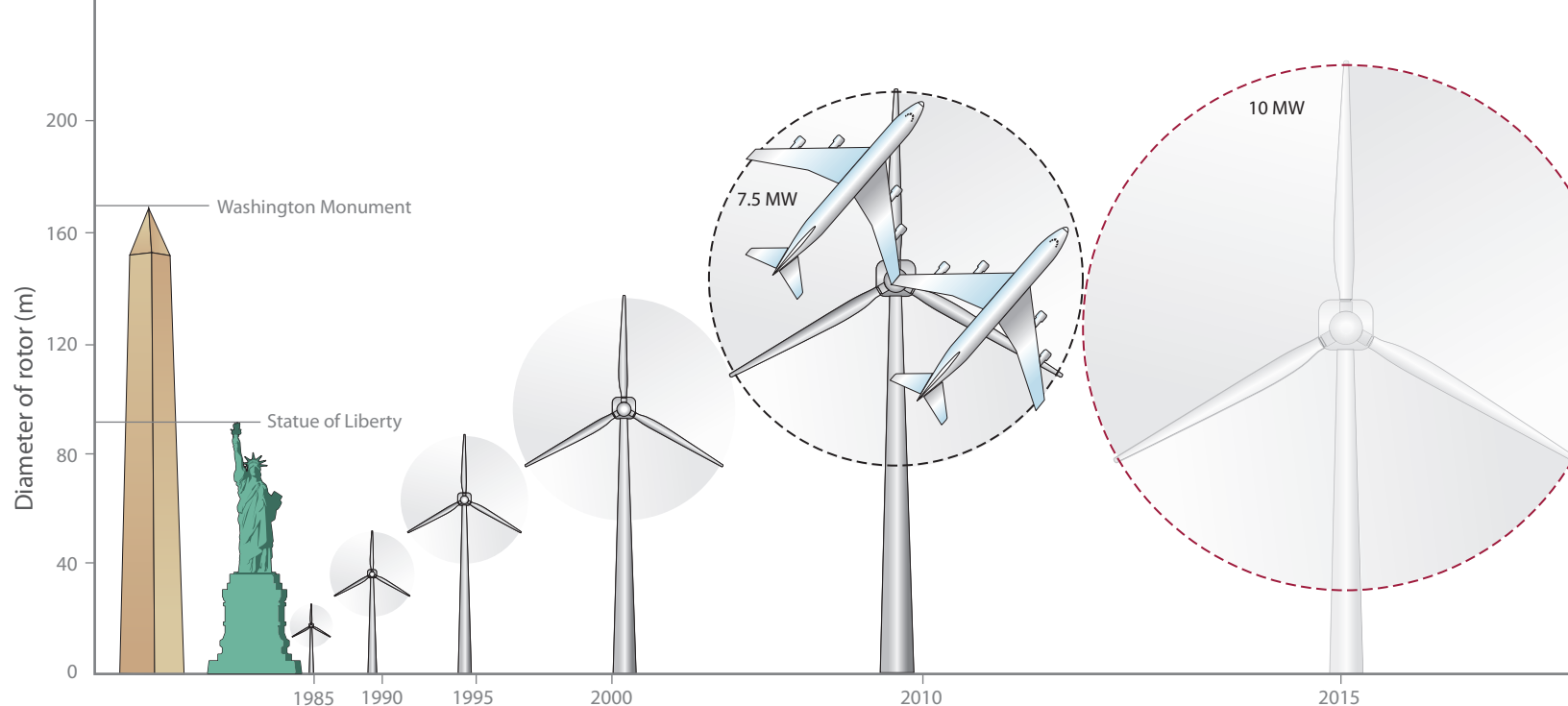
“Unfortunately, the growth of wind turbines has outpaced power companies’ knowledge of their dynamics within wind farms,” says Curtt Ammerman, the head of a Los Alamos research team striving to make wind turbines more effective.

Size isn’t everything

The largest wind turbines in operation today stand on towers 135 meters (m) tall and have rotating assemblies, or rotors, 126 m in diameter (including the blades). To put that in perspective, the wingspan of a Boeing 747 jumbo jet—similar to the one the U.S. president flies around in—is only 64 m, or about half the diameter of the turbine rotor. The diameter of a wind turbine from the early 1980s was about one-tenth of what it is now. And rotors continue to grow even bigger: a 10-MW offshore model with a whopping 190-m rotor diameter is currently under development.

What’s the problem with such a large-diameter wind turbine? Standing by itself in a perfectly smooth flow of wind, nothing. But in a turbulent flow, whether that turbulence is caused by the weather or by the wake from another large turbine positioned upstream, a large diameter can become a liability. Any differential force applied near the ends of such long turbine blades can produce severe bending stresses in the blades and a tremendously amplified torque at the center, where the system’s gearbox and electrical generator reside.

“These big, beautiful, modern wind turbines have a design life of 20 years and yet break down, on average, two or three times in the first 10 years,” says Ammerman.



Wind turbines have grown rapidly in the past two decades in order to meet the rising demand for renewable energy. But with larger sizes come not only more power, but also larger torques, more frequent damage to the central hub, and higher repair costs.

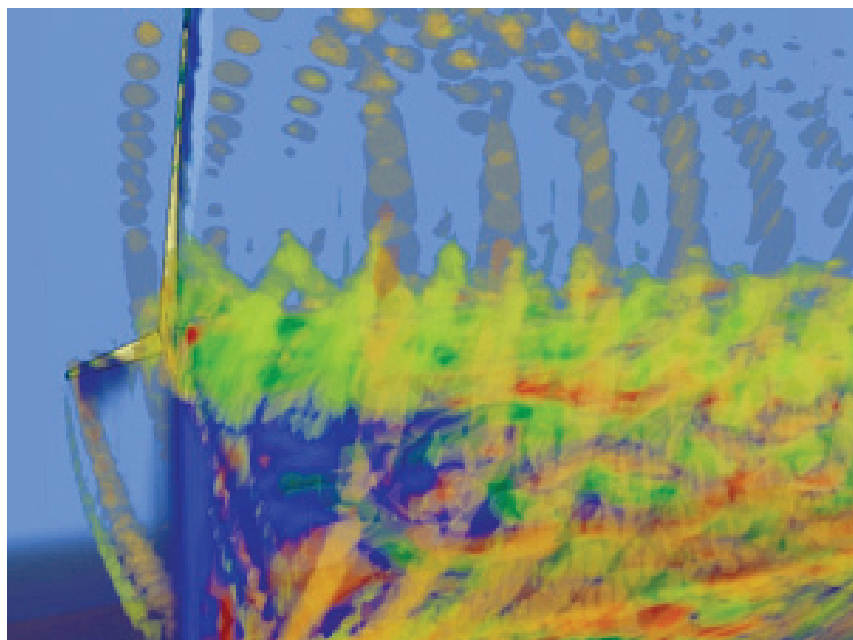
Not surprisingly, most of the downtime-causing damage suffered by wind turbines in the field afflicts their gearboxes (60 percent), generators (14 percent), and rotor blades (7 percent). Just as a long-handled wrench makes it easy to turn a nut, a long-blade turbine makes it easy for turbulent wind to monkey with the gearbox and generator—which is partly why it’s so common to see wind turbines that aren’t spinning. (Other times, the arrangement of turbines and the path of the wind can combine to produce temporary dead spots in the airflow.) Long turbine blades and correspondingly large diameters provide a great deal of leverage, which, of course, is desirable when it is applied to turn the rotor as intended. But when a turbulent wind stream twists the rotor out of its plane of rotation, then leverage can turn into damage.

To make matters worse, it’s no simple matter to repair a damaged gearbox behind the central hub of a turbine rotor when it’s one-and-a-half football fields off the ground. According to Ammerman, it’s not unusual for it to cost more than a quarter-million dollars just to get a crane large enough to reach the hub of a damaged turbine out to the site; the cost to repair or replace the broken component comes on top of that.

“That’s why you’ll often see multiple turbines not spinning, instead of just one,” he says. “They’re so expensive to repair that it’s more economical to wait until a number of them are broken before getting a crane to fix them all at once.”

Bumpy ride

Rod Linn and Eunmo Koo are atmospheric modelers on Ammerman’s team. They figured out a way to repurpose a supercomputer-based simulation tool originally designed to model the evolution of wildfires into one that analyzes the interaction between spinning turbines and the wind around them. Within this numerical simulation, called WindBlade, it is possible to vary any number of parameters to obtain realistic results, including the turbines’ power output and the forces on the blades—and therefore the torques delivered to the hub as well. A wide range of scenarios can be tested,



The turbulence in the wake of a modern wind turbine is predicted by the Laboratory’s WindBlade supercomputer simulation.

including wind flow that's uneven, gusty, turbulent, or shifting around in direction.

The parameters of the wind farm can be adjusted as well by varying the size, number, and arrangement of its turbines. In addition, the turbines can occupy a variety of landscapes by introducing hills and even heterogeneous vegetation. (Such complex supercomputer modeling is a major component of what Los Alamos brings to the table in wind energy and other research.)

The simulation results were eye-opening. They showed, for example, that a large wind turbine positioned somewhere behind the front row in a wind farm would experience stresses that varied wildly—not just in time, but also from one blade to another, and even from one part of a blade to another. These stresses would shift about quickly, growing and shrinking by nearly a factor of 10 over a period of seconds. Harmful vibrations in the turbine blades and sharp jolts on the central gearboxes were commonplace.

"I remember being taken aback by how much the mechanical stresses could fluctuate between the turbine blades from one moment to the next," Linn says. "And nobody had developed a thorough understanding of the nature of these loads or the turbulence that causes them, especially in a wind turbine array where numerous turbines are impacting each other."

Perhaps if the wind-power community had that understanding all along, they might have thought twice about meeting the ever-larger energy demand with ever-larger turbines. Or perhaps larger turbines would have proved to be the best option regardless. But even in that case, results from high-performance computing simulations like WindBlade could help engineers to make their designs more robust—or at least set their performance expectations more in line with the reality of turbulent airflows.

Large-diameter turbine rotors chew up the airflow for any other turbines located downstream. WindBlade revealed that after a 15-meter-per-second (m/s) wind passes through a 5-MW turbine, the wind speed immediately drops to about 10 m/s. It slowly regains speed as it flows downstream due to the entrainment of the surrounding wind (wind that didn't pass through the rotor) mixing in with it. But this return to the initial wind speed doesn't happen until well after 14 rotor-diameter-lengths downstream. That is, for a 100-m diameter rotor, the wind wouldn't recover to its original speed until a distant 1.4 kilometers behind the first turbine.

Of course, in the real world, not many wind farms can space their turbines kilometers apart. Often the spacing is more like seven rotor diameters and sometimes as close as three. WindBlade simulated a series of 5-MW turbines,



The largest wind turbine in use today is 135 meters tall at the hub and 126 meters in rotor diameter.

one behind the next at a variety of spacing intervals to examine the sensitivity of power output to spacing. In one simulation with three-diameter spacing, the five turbines were exposed to a 15-m/s headwind (at hub height). The second turbine saw wind at about 10 m/s, as expected, but the third got only about 7 m/s—a huge drop from the initial 15 m/s. Then the wind speed rose a bit, leveling off for the subsequent turbines at around 8 m/s, as more wind from above the turbines mixed in, due to a combination of ambient and turbine-induced turbulence.

Best foot forward—or not

Why does the wind speed matter? Because in the theory of wind energy, the power a wind turbine produces is proportional to the wind speed cubed. If the wind speed gets cut in half—from the first turbine in Linn's simulation to the third, fourth, and fifth, for example—the power drops to a factor of one-half cubed, or one-eighth, of its full-speed level. In reality, the situation is more complex, and there isn't just a single, uniform wind speed approaching a rotor 100 or more meters in diameter. Regardless, a substantial power loss remains. For the simulation of five turbines staggered at three rotor

diameters apart, the total power produced was only around 15 MW, not the 25 MW one might expect from five 5-MW turbines.

The team then repeated the previous experiment but changed one thing: they restricted the first turbine to 4 MW and kept the others at 5 MW. In real life, this could be accomplished from the control room; operators can adjust the pitch of the turbine blades (twist them) to extract less power and suffer less mechanical stress. Interestingly, they found that the combined power from all the turbines was actually greater as a result of the power restriction. This demonstrates the possibility of optimizing a wind farm and even reducing its original installation cost by placing smaller wind turbines in forward positions and regularly varying the blade pitch on different turbines to maximize the power generated by the farm overall as wind conditions change.

“That’s where we want to go next,” Linn says. “We want to provide tools and understanding that can improve the performance of existing wind farms, enhance the design of future wind farms, and supply new operational software to help the utilities run their wind farms at peak performance with minimal damage.”

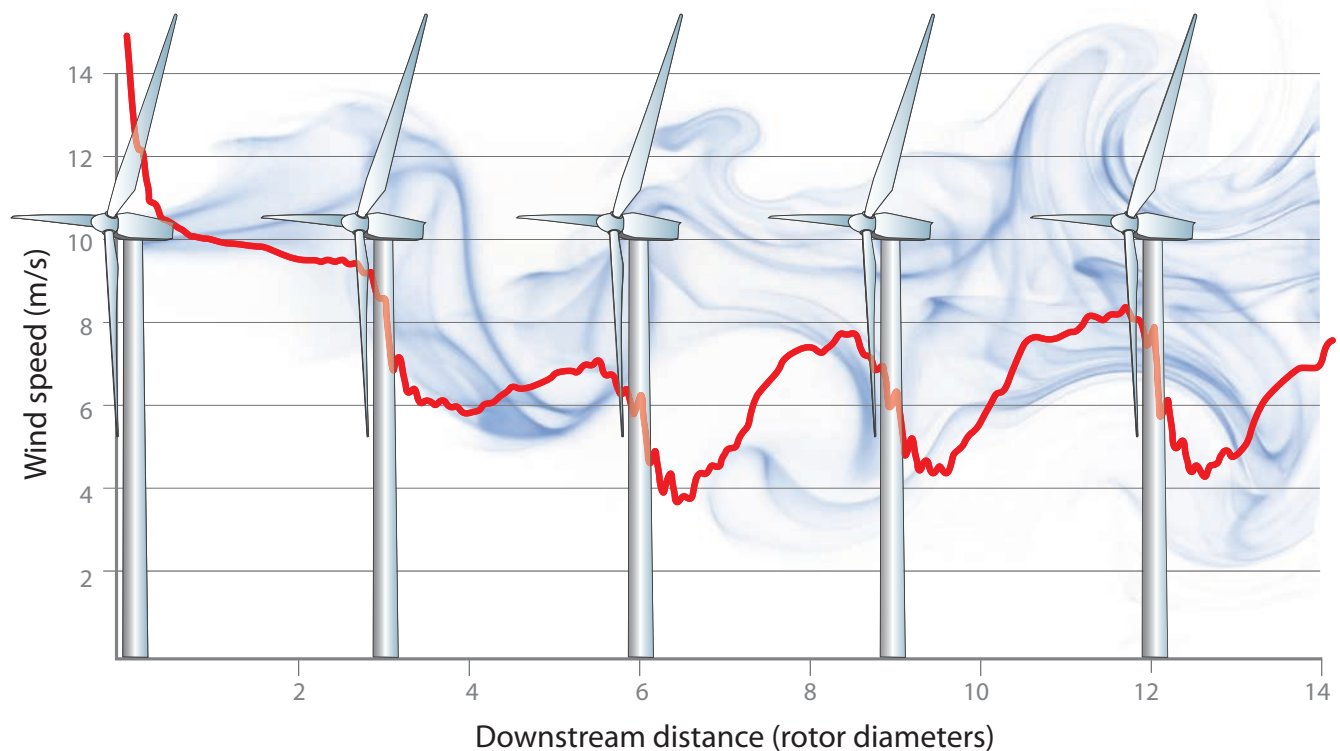
Such future software could tell operators when and how much to adjust the blade pitch on each turbine, moment by moment, to increase the power produced by the farm as a whole. It could also compute detailed stresses and torques and instruct operators to take action to prevent excessive damage accumulation on individual turbines under certain

conditions. In fact, many of these improvements could be automated, with adjustments being made whenever various sensing systems detect changing wind patterns or mechanical stresses.

The Department of Energy (DOE) has set ambitious goals for wind power and will need advances like these to get there. It seeks to increase wind energy from a current 4 percent to 20 percent of the nation’s total electrical consumption by 2030. The goal appears to be achievable; Iowa, South Dakota, and Kansas already obtain more than 20 percent of their electricity from wind. But even the comparatively paltry 4 percent for the nation as a whole has been achieved with a dramatic expansion of wind power installations in recent years. Getting to 20 percent nationally will require a continued increase in wind power installations to be sure, and it will also require improving wind farms’ output-to-cost ratio, particularly by reducing turbine downtime. Otherwise, turbine repairs will remain too frequent and too expensive for wind energy to adequately displace fossil fuels.

“The DOE’s 20 percent plan is an important one, at the same time reducing our carbon footprint and our reliance on foreign fuels, for better energy security,” says Ammerman. “Fortunately, most of the turbine failures that currently hold us back from meeting that goal take place in the gearbox, generator, and blades—the same components our research can help to protect.” **LDRD**

—Craig Tyler



Five simulated 5-MW turbines in a row, spaced three turbine diameters apart, produces a rapid loss of incoming wind speed that eventually levels off with about half of the initial wind speed reaching the turbines in back.